Pressures of Partial Crystallization of Magmas Erupted Along Transform Faults in the Atlantic Ocean

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Table of Contents

Abstract

Crystallization of magmas at mid-ocean ridge transform faults remains a little-studied and poorly-understood phenomenon. Although some crystallization pressures calculated for magmas erupted along transforms transecting the northern part of the East Pacific Rise are anomalously high compared to those erupted along normal ridge segments, the conditions of crystallization of magmas along transform faults as a whole remain unknown. Using data compiled for lavas erupted along five transform faults that cross-cut northern Mid-Atlantic Ridge, crystallization and pressures were calculated and compared to each other to fully understand what processes might be occurring. Overall the magmas are found to have pressures within the range of those expected for intra-crustal crystallization, and the magmas appear to have evolved by normal crystallization processes. Some samples yield anomalously high pressures of partial crystallization, but these samples also show unusual chemical characteristics, and therefore the calculated pressures cannot be accepted as recording the actual pressure of crystallization.

Acknowledgements

This paper is dedicated to all who helped in its creation. First and foremost credit goes to Langmuir, Gale and co-workers for compiling the geochemical data base, without which I would not have been able to begin the research. Without data, there is no research, so their contributions are immeasurable to my success. Thank you to my research professor Dr. Michael Barton, who was always encouraging and had good things to say on my work. It was in his petrology class that I had my first real exposure to magmatic processes and where I found my interest in plate tectonics. Through all the trials and tribulations of finishing this paper he was available to provide support for both editing and interpretation. Thank you also Chrissy Zerda for helping me with the data and providing support along the way. And very big thanks indeed to Lienne Sethna, who worked through mineralogy and petrology with me and was the impetus for me to pursue this particular research with Dr. Barton. Thank you to my major advisors Dr. Karen Royce and Anne Carey, and to my family, who provided much needed support and steady hands to guide me through my final semester. And last but not least, thank you to the laws of physics for not failing this year and ruining my research.

List of Figures

Introduction

Of the myriad geologic processes that shape our planet, few can be said to carry as much importance as plate tectonics. Plate tectonics quite literally shapes the face of the world as we know it. Mountain ranges rise and fall, oceans open and close, and the very land we live on moves across the globe all because of plate tectonics. In some ways this power is easily observed; we can study a mountain range right down to individual lithostratic units, charting their growth and evolution over time. Fossil evidence can help us to patch together ancient shapes of continents, and magnetic evidence in the rocks can trace the courses they took to move apart. Yet for all this knowledge that we have gained over the course of centuries of study there is one place that, due to inaccessibility, has remained largely untapped: Mid Ocean Ridges.

In recent decades, numerous expeditions, using a variety of methods, have shed light on this mysterious area. Sonar mapping spurred on by World War II and the Cold War has revealed the topography of the ocean floor; magnetic surveys of the ocean basins have proved that mid-ocean ridges are the sites of seafloor spreading. Drill samples, taken from the seafloor, indicate the composition of rock formed at these ridges. And yet for all these advances, there is still much that we don't know, and it is these gaps of knowledge that modern studies seek to fill.

This research aims to help fill a certain gap in knowledge: transform faults. Using geochemical datasets collected from transform faults along the Mid Atlantic Ridge, we have calculated the pressures of partial crystallization of magmas erupted along these faults, which provides insight into the formation of oceanic crust. This provides a clearer picture of processes that occur at transform faults.

Geologic Background

Mid-ocean ridges (MORs) are perhaps the most important areas of geologic activity on the earth. In their simplest form they are regions of separation between crustal plates where magma rises up from the astenosphere and solidifies to become new crust. As the plates are pulling apart at MORs, the crust and lithosphere become much thinner than anywhere else on the globe. The thinning of the stretching lithosphere causes decompression melting of the underlying mantle, generating basaltic magma from the rift (Bonatti, 2003). Because basaltic magma is much denser than felsic magma, oceanic crust will lie at a lower elevation than continental crust (Whitmarsh, 2001). This discrepancy is what forms oceans, as the denser basaltic crust lies below sea level, and any new rift systems are quickly covered in water.

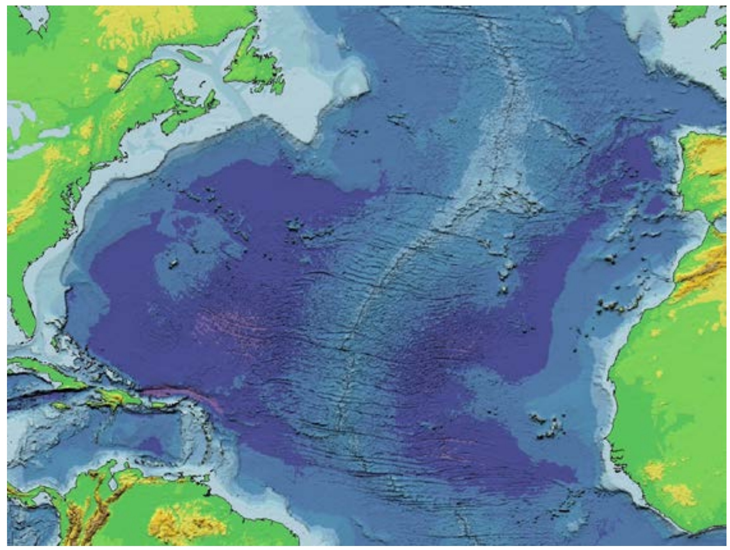


Figure 1: Map of northern Mid Atlantic Ridge

Ridges themselves come in two main types: fast- and slow-spreading. Fast-spreading ridges, such as the East Pacific Rise, generally show greater amounts of uplift along the ridge and a gentler slope away on either side. A slow-spreading fault on the other hand, while still displaying uplift in areas around the ridge, will feature an axial rift valley surrounded by steep normal faults (Macdonald, 2001). Ocean crust around slow-spreading ridges appears to be more fractured in general.

As can be seen from a map of the seafloor, MOR's do not follow straight, uninterrupted lines. Rather, they are divided into many small segments joined together by transform faults. While the fracture zones in the crust from these faults can be seen on the ocean floor for thousands of miles on either side of the ridge, in actuality they are only tectonically active between the ridge segments where plates are pulling in opposite directions. This was not always the case; original hypotheses for these faults suggested that ridges originated as continuous lines which over time split apart into segments as the varying sections travelled at differing rates. However, studies show that the age of the seafloor is actually continuous across the extended faults, and that no relative movement occurs there. This might seem to be a rather unimportant detail in the history of the study of mid-ocean ridges, but it is actually crucial to understanding what is occurring in these transform faults. The only true location of the faults, and their associated seismic activity, is between the ridge segments, where the opposite plates grind against each other as they pull apart. But while this provides a glimpse to the processes occurring at transform faults, it doesn't explain their presence within the ridge. In fact, these transform faults aren't even the only type of offset that occurs along mid-ocean ridges. These offsets, known collectively as ridge axis discontinuities (RADs) come in a variety of forms, from larger transform faults to overlapping spreading centers

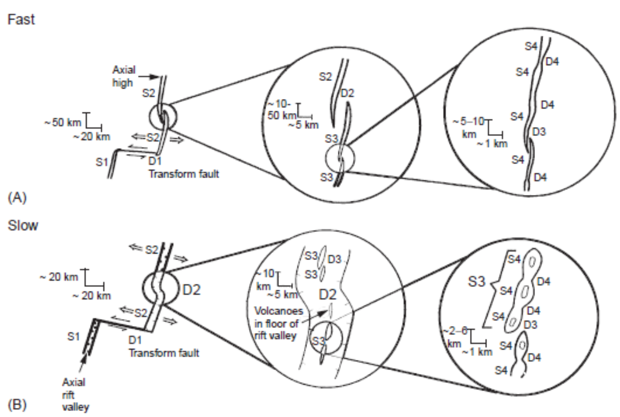


Figure 2 Types of RADs at (A) fast- and (B) slow-spreading ridges

and even small mobile breaks in the ridge (Macdonald, 2001). Although numerous studies have been made on these discontinuities, their presence still remains a mystery. Some studies that focus on magma supply seem to suggest that perhaps magma supply at these discontinuities is reduced relative to that along normal ridge segments. These studies found that erupted magma volume is a maximum in a cross-sectional area of the ridge near the centers of ridge segments, and that higher concentrations of volcanoes occurred in the shallow midsegment area than at the segment ends (Macdonald, 2001). This pattern holds true for both fast and slow spreading ridges. These studies also utilized crustal magnetization, which was much greater near segment ends indicating an area locally starved for magma, but in the presence of magma supplies rich in iron. This isn't the only geochemical evidence in support of this theory. MgO concentrations (in wt%), which correlate positively with eruption temperature and, perhaps, greater local magma budget, also show a correlation with the axial-cross-sectional area, and hydrothermal venting (as measure by geochemical tracers and light backscatter) also varies directly with the cross-section (Macdonald, 2001). These results are mostly applicable to fast-

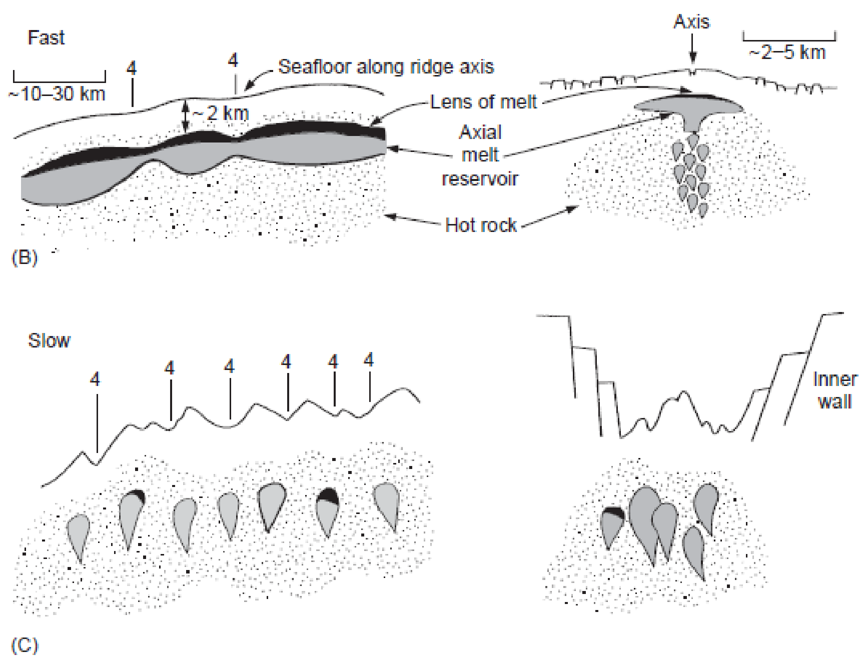


Figure 3: Parallel and perpendicular cross-sections of fast- and slow-spreading ridges showing discontinuities (numbered) and magma sources

spreading ridges, but slow-spreading ridges also show similar results from seismic and gravity data that suggests oceanic crust thins greatly near transform faults.

A possible explanation for this is that mantle upwelling is highly focused near mid-segment regions, with very little near the ends, again suggestive of a magma-starved region. However, another theory has also been presented where the crustal thickness variations are actually the result of mechanical thinning due to faulting. As there is no conflict between both models, it is impossible to say from existing studies which theory, if either, is correct, or whether both are correct to some degree. Regardless, this crustal thinning is largely absent from the faster-spreading ridges. To explain these findings, it has been suggested that fast-spreading ridges contain large, continuous chambers of magma that thin out slightly at discontinuities, and slow-spreading ridges have individual chambers between the discontinuities, and there is little magmatic activity along the latter. Nevertheless, it is clear that the processes occurring at transform faults are still not completely known which is the reason for this study.

Previous studies of the Reykjanes, Juan da Fuca and from the Northern Pacific Rise ridges indicate anomalously high pressures of crystallization near transform faults (Scott et al., 2010, 2012, 2013; Zerda, 2014). The calculated pressures range up to 1000 M Pa, and are much higher than the average pressures of partial crystallization (200-300 M Pa) calculated for normal ridge segments. These results appear to confirm the hypothesis of Herzberg, (2004), that magmas along transforms partially crystallize in both the crust and upper mantle, and that the high pressures of partial crystallization reflect the fact that the deep crust and upper mantle are cooler along transforms than beneath normal ridge segments. In an effort to further test this hypothesis, this study focuses on magmatism along transforms in the North Atlantic.

Methods

The most time-consuming aspect of this research was organization of the data. All glass compositions were taken from two sources: the Gale et al (2013) compilation of MORB compositions and the PetDb online rock database (www.petdb.org).

Five transform faults were chosen for study. Atlantis lies at about 30° North, Famous at 35° North, Kane at 23.8° North, and Vema at 11° North. 15 North is the only region that has never been well studied before or given a name, and was thus named after its latitude, 15° North. Compositions lying along these transforms were identified using the program GeoMapApp. Compsitions for samples that lay along ridge segments adjacent to the transform faults, or on seamounts, were excluded. The resulting data sets were edited to exclude duplicate analyses and incomplete analyses.

The Edited data sets were used to calculate pressure of crystallization using the method described by Kelley and Barton (2008). The following relationship between pressure (P, in megapascals) and depth (z in meters) was used to calculate the depth of partial crystallization:

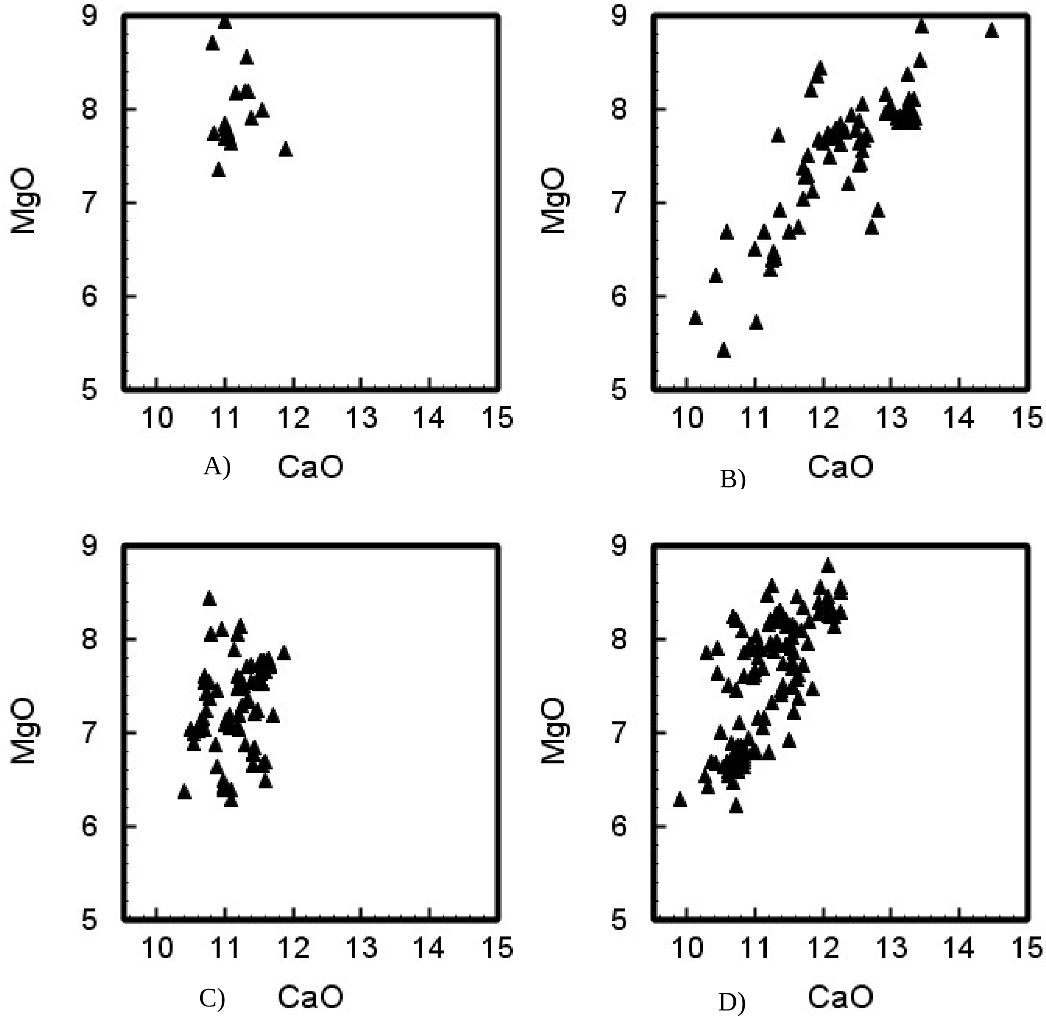
$$P = \rho g z$$

with ρ as the density of oceanic crust (2900 kg/m^3) and g as acceleration due to gravity, 9.81 m/s^2. This calculation took into account the effect of the column of seawater using a density of 1000 kg m^{-3} for seawater. The correction for the column of seawater converts all depths to depths below the seafloor and is necessary for comparison with the results of seismic studies.

Results

The methods used to calculate the pressures of partial crystallization are calibrated for liquids in equilibrium with the mineral assemblage olivine-plagioclase-clinopyroxene (opc). Therefore, it is necessary to identify melt compositions that crystallized the opc assemblage. Such compositions will show a linear, positive relationship between MgO and CaO on variation diagrams. The plots in Figure 4 show that this condition is fulfilled for the Famous, 15 North, and Vema transforms.

Plots of pressure versus longitude (Figure 5) indicate that pressures of crystallization are relatively constant along each transform, whereas plots of pressure versus MgO (Figure 6) indicate that pressure remained either constant, or decreased slightly, as magmas crystallized.



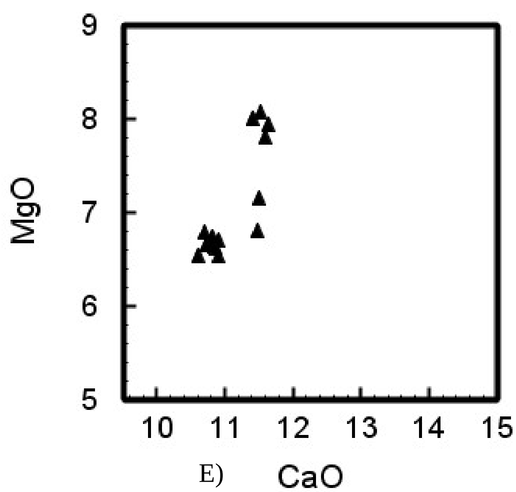


Fig. 4 Plots of CaO vs. MgO levels for A) Atlantis, B) Famous, C) Kane, D) 15 North, and E) Vema. Note the positive relationship seen in Famous and 15 North

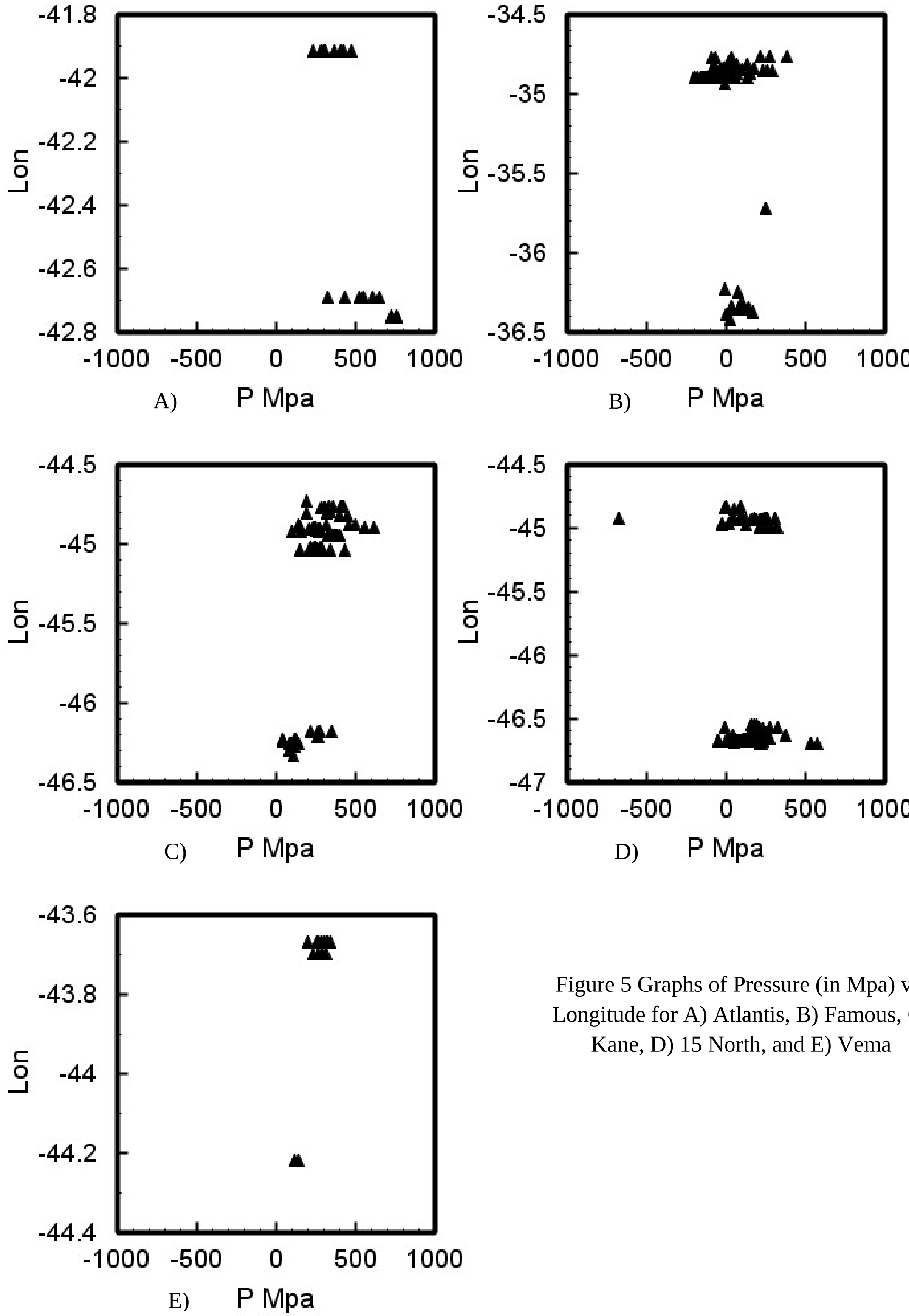


Figure 5 Graphs of Pressure (in Mpa) vs. Longitude for A) Atlantis, B) Famous, C) Kane, D) 15 North, and E) Vema

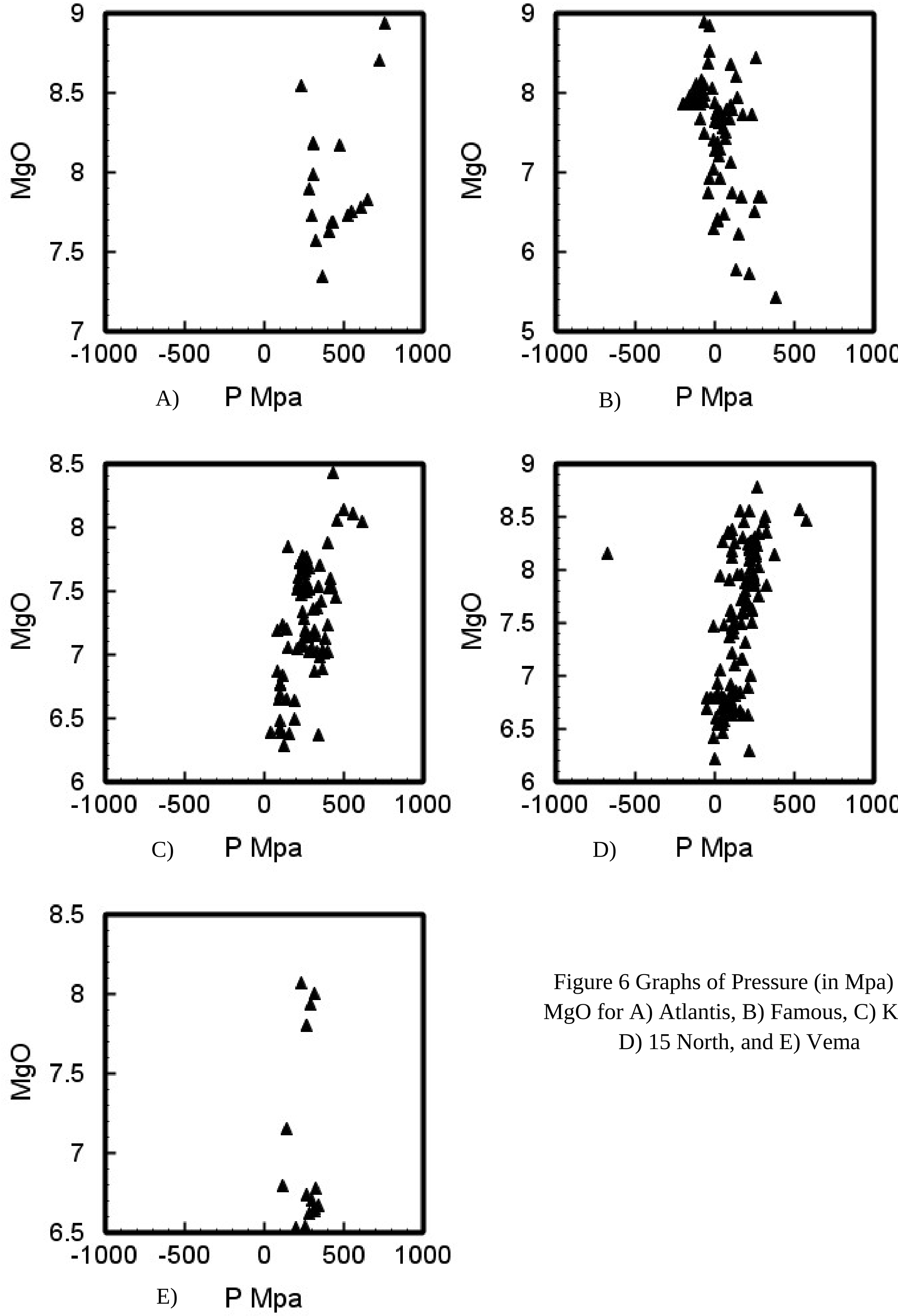


Figure 6 Graphs of Pressure (in Mpa) vs. MgO for A) Atlantis, B) Famous, C) Kane, D) 15 North, and E) Vema

Discussion

Some of the pressures calculated for the initial data sets are meaningless because they are either negative or are associated with large errors (126 MPa – the error deemed acceptable by comparison with experimental data). All pressures more negative than -126 are filtered out of the data, whereas pressures between -126 and 0 are changed to 0. Samples with positive pressures with an error greater than 126 MPa were also filtered out of the results. Finally, global xtudies of MORB show that samples with MgO contents greater than 8 wt. % do not lie along the liquid-olivine-plagioclase-clinopyroxene cotectic, so that such samples were also filtered out of the results.

Graphs for the filtered results (P versus longitude and P versus MgO) indicate that pressures are usually at or below 300 M Pa for three transforms (Famous, 15 North, and Vema) which is similar to pressures calculated for normal ridge segments (Scott et al;, 2010, 2012, 2013). Note that samples for these three transforms show a linear, positive relationship between MgO and CaO on variation diagrams consistent with magma evolution via crystallization of olivine, plagioclase and clinopyroxene. The results for these transforms are therefore considered to be robust and reliable.

For the other transforms (Atlantis and Kane) the results indicate higher pressures of crystallization, up to 600 M Pa. The samples for these transforms do not show a linear, positive relationship between MgO and CaO on variation diagrams, and the compositions of these samples are not, therefore, consistent with magma evolution via crystallization of olivine, plagioclase and clinopyroxene. The results for Atlantis and Kane are not therefore considered to be robust or reliable, and it is considered unlikely that the calculated pressures of partial crystallization reflect **the actual** pressures of partial crystallization.

Based on the results obtained in this work, it would seem that, for the most part, pressures along transforms are not anomalously high compared with those along normal mid-ocean ridges. Transform faults are not as anomalous as previously believed. Very few of the pressures calculated in this work are anomalously high, and the high pressures are calculated for samples with unusual chemical characteristics, so that the results for these samples are not deemed reliable.

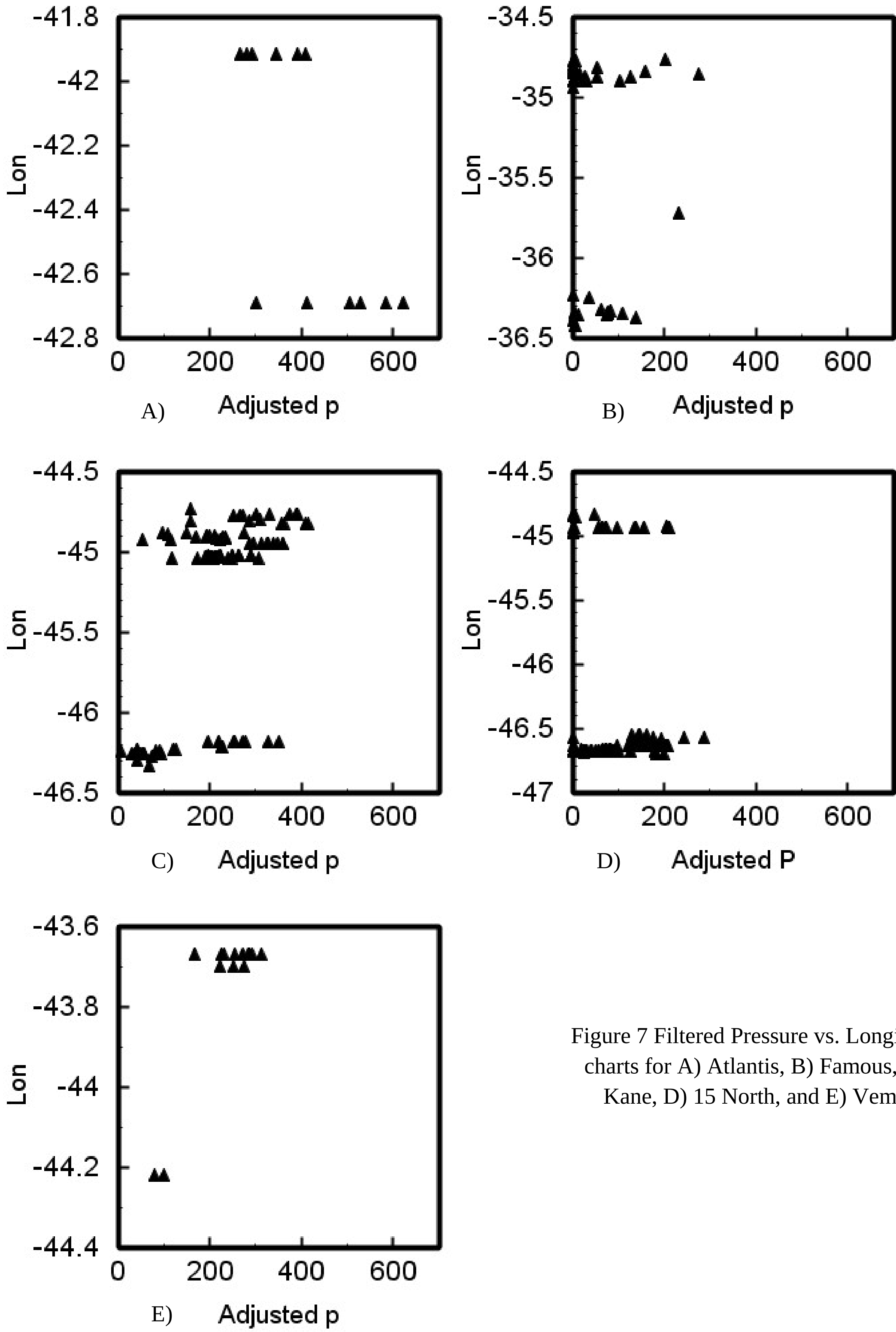
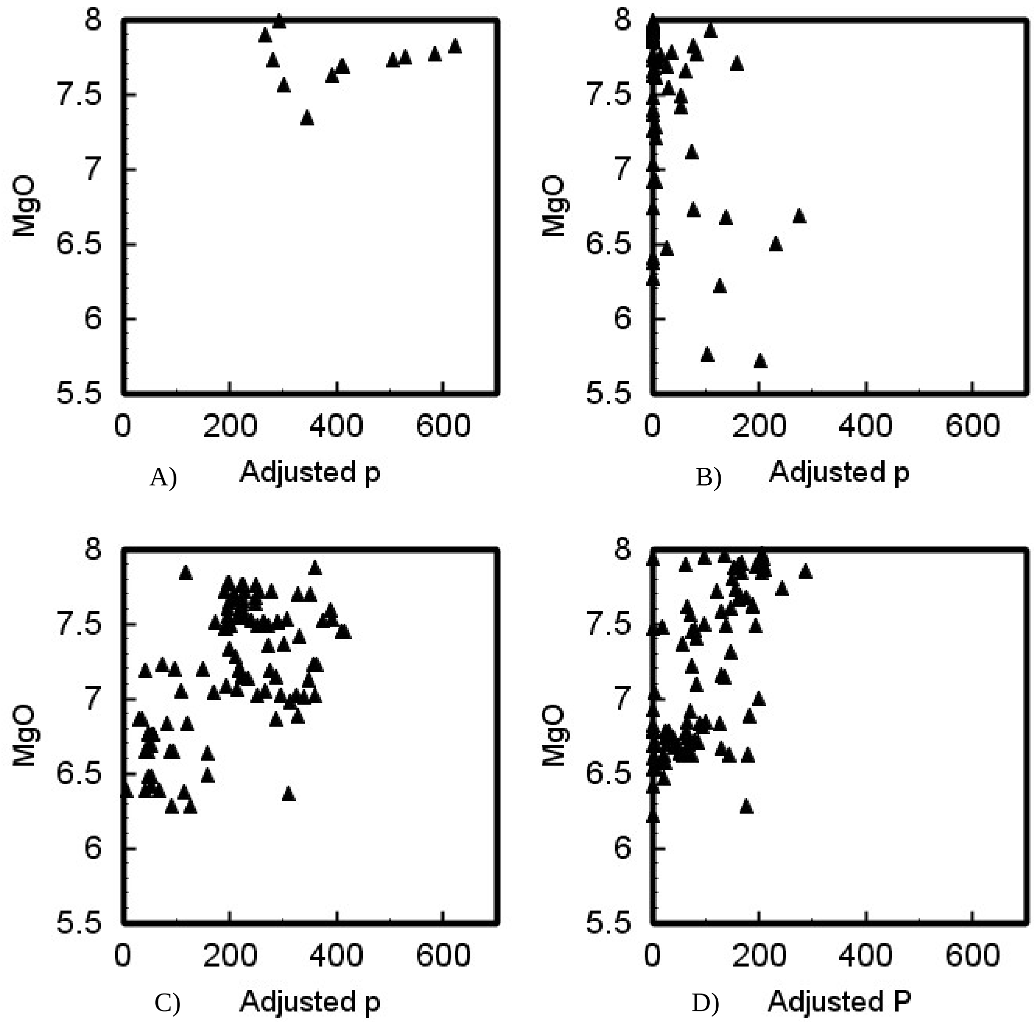


Figure 7 Filtered Pressure vs. Longitude charts for A) Atlantis, B) Famous, C) Kane, D) 15 North, and E) Vema



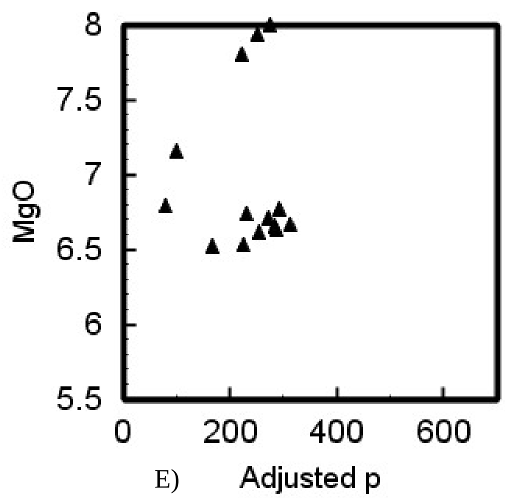


Figure 8 Filtered Pressure vs. MgO charts for A) Atlantis, B) Famous, C) Kane, D) 15 North, and E) Vema

Ideas for Future Research

The most logical extension of this research is to use the results found here to explore the reason(s) that some samples have anomalous chemical compositions and yield unrealistically high pressures of partial crystallization. Of course, this is no easy task, because the processes responsible for the anomalous chemical compositions and associated anomalously high pressures occur deep under the ocean floor. However, combining the results of petrological studies to determine the pressures of partial crystallization with geochemical studies of the same samples to constrain models of magma evolution offers promise for identifying the process(es) responsible for producing the anomalous magma compositions. Such studies have been initiated by researchers at OSU using samples from the northern EPR (including the Clipperton and Siqueros fracture zones) and from the Famous region in the Atlantic.

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